Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 145 (2016) 136 – 143

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

A Nearshore Heaving-Buoy Sea Wave Energy Converter for Power Production

Joseph Youssef[a], Jean Matar[a], Pierre Rahme[b], Charbel Bou-Mosleh[a,]*

[a]*Notre Dame University-Louaize, Zouk Mosbeh, Lebanon*
[b]*Lebanese Univesrity, Roumieh, Lebanon*

Abstract

There exists nowadays an ever-increasing demand for clean and renewable energy, due to the high level of pollution conventional energy production plants produce. Extracting energy from sea waves in Lebanon is a technology that has not yet been developed. In this paper, the potential of harvesting wave energy to produce electrical power on the Lebanese shore is investigated. As such, a compact wave-harvesting device was built. It consists of a float-rack-pinion system that transmits the vertical heaving motion of the waves and converts it into a rotating motion. This in turn is used to produce electricity through an alternator. A prototype was built and successfully tested in shallow water near shore to light up a 3-W lamp. The mechanical design of the manufactured device along with the operation process will be presented in details. In addition, the test results will be summarized along with the potential improvements that can be applied to the system.

Peer-review under responsibility of the organizing committee of ICSDEC 2016

Keywords: Green Energy; Wave Energy Converter; Heaving Buoy; Rack-and-Pinion

1. Introduction

Renewable energy is the energy generated from natural resources which are replenished such as wind, solar, biomass, and tidal power. Researchers are investing heavily nowadays (time and money) in designing and improving renewable energy devices, some of which are wave energy harvesters ([1],[2],[3]). Wave energy is one of the most

* Corresponding author. Tel.: +961-9-208-430; fax: +961-9-218-771.
E-mail address: cboumosleh@ndu.edu.lb

Peer-review under responsibility of the organizing committee of ICSDEC 2016
doi:10.1016/j.proeng.2016.04.032

available and consistent energy all year round. It has many advantages over other types of renewable energy. The most obvious advantage of wave energy over solar energy for example, is that it is available at night and not only during the day.

Several authors have studied different types of wave energy converters ([4],[5],[6]). It is important to note however that many of these devices are still in the research and development phase and has not yet been used at production level. Falnes in [7] proposed different types of wave-energy converters. Kofoed et al. [8] also proposed three different projects of wave energy converters. These converters are Wave Dragon, Wave Star and Seawave Slot-cone Generator. The concept of the Wave Dragon works by waves overtopping a ramp, filling a floating reservoir with water a higher level than the mean sea level. The Wave Star is equipped with a number of floats which are moved by the waves to activate pumps. The Seawave Slot-cone Generator is an overtopping based wave energy converter utilizing a total of three reservoirs placed on top of each other. Hybrid systems have also been considered in different other studies ([9], [10], [11]), where one system works in parallel with other systems at the same time to enhance the power production.

To generate an improved amount of power, Wave Energy Converters can be arranged in several rows or in a “farm” [12]. Hong et al. [13] presented a review of strategies for electrical control of wave energy converters as well as energy storage techniques. In this review, different types of wave energy converters are classified by their mechanical structure and how they absorb energy from ocean waves. Several authors analyzed the wave energy resource theoretically and practically available in a sea of moderate depth ([14], [15]). This part of wave energy is quite important; however in this work it will not be tackled.

In this work, a wave energy harvester is presented. First, the system design is explained. The different components of the system as well as the operation process are then detailed. Finally, the manufactured system is presented as well as the testing results.

Nomenclature

S_{ut}	Ultimate Strength (MPa)
S_y	Yield Strength (MPa)
WEC	Wave Energy Converter

2. Wave Energy Converter Design

The proposed wave energy converter (WEC) is based on a previous successful design investigated by Bou-Mosleh et al. in [16]. The device is mainly designed to function in the weak wave energy conditions near the Lebanese shore. In fact it was designed to work in shallow water ($1\,m - 5\,m$). Lebanon is located on the Mediterranean Sea where the minimum average monthly significant wave height at Beirut coasts is about $0.5\,m$ in June as shown in Fig. 1 (expecting even lower values for the actual wave height).

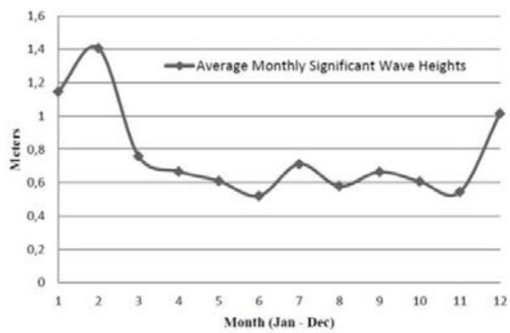
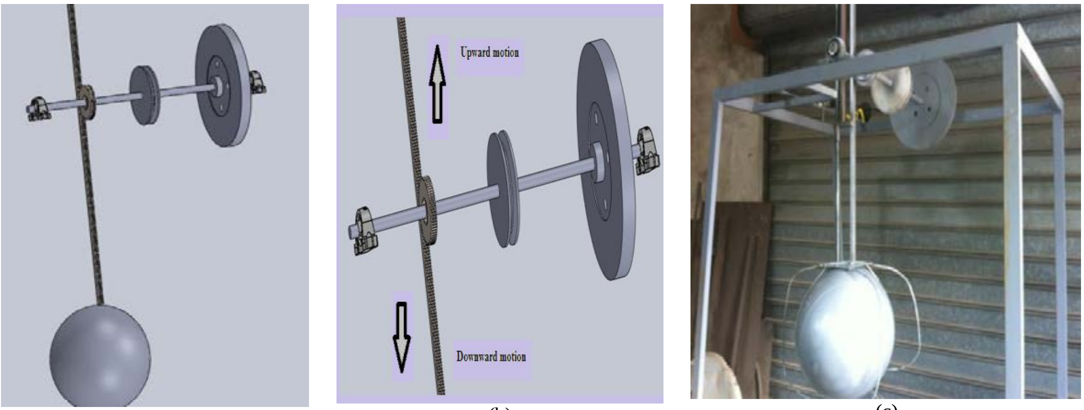


Fig. 1. Average monthly significant wave heights [17]

A simple design was initially investigated (see Fig. 2). It basically uses a float connected to a rack and pinion. This in turn is mounted on a shaft, to which a flywheel is attached, and connected directly to an alternator. This combination exploits the heaving motion of the waves and transforms it into a rotational motion. The pinion is connected to the shaft through a one way bearing, thus the shaft is engaged during the upward motion of the wave (as shown in the figure) and is free to rotate under the action of the kinetic energy stored by the fly wheel during the downward motion.

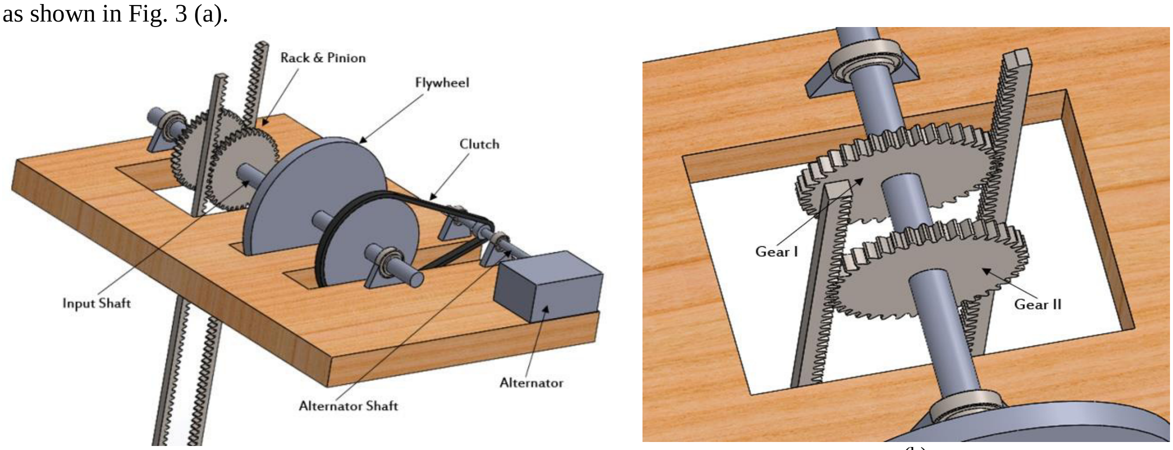


(a) (b) (c)

Fig. 2. Initial wave energy converter: (a) and (b) design, (c) prototype

The shortcoming of this design was that it does not exploit the downward motion. There was approximately three seconds between each upward motion. Therefore, if on a given day the wave period exceeds the three seconds, the flywheel may not keep rotating in order to power the lamp. In the current work, an attempt to recover this time was tackled. The idea was to use another and similar rack-and-pinion system for the downward motion. This will probably assure that whatever the duration of the period is, the overall system, and during the downward motion, will provide the rotation needed to generate electricity till the next upward motion.

As a result and in an attempt to improve the design and take full advantage of both the upward and downward motion of the float, two freewheel gears (instead of one) were mounted on a shaft connected directly to the alternator as shown in Fig. 3 (a).



(a) (b)

Fig. 3. Proposed wave energy converter: (a) whole system, (b) gears

The two gears are mounted in opposite directions (see Fig. 3 (b)) in such a way that the shaft will be engaged to one free wheel during the upward motion (under the action of buoyancy forces), and to the other one during the downward motion (under the action of the floating part's weight). The shaft rotates in the same direction during both upward and downward motion. The detailed mechanism of the system is summarized in Fig. 4.

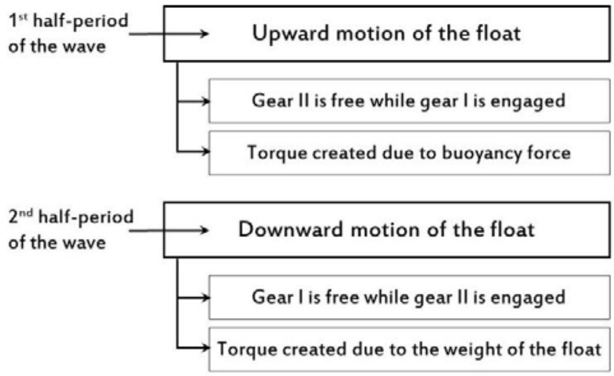


Fig. 4. Mechanism of the system

The dimensions of the system are $75 \times 75\ cm$, and each rack's length is $75\ cm$.

To better understand the mechanism of this device, key design criteria that led to the selection of the different components will be summarized. The function of the various device components and their contribution to the successful operation of the device will also be presented.

2.1. Gears

The designed system consists of a rack driven by the wave force. It will generate a torque to rotate the pinion gear and turn the shaft. In such application spur gears that carry radial forces can be used as well as helical gears that carry both radial and thrust forces. Since only radial forces were of interest, a spur gear with a module of 1 was selected. Both gears were chosen to have a radius of $2\ cm$.

The gears can be made of several materials such as steel, stainless steel, polyamide and others. Corrosion is a major problem because the system is to be installed on shore. In the current work, the plan was to build a small scale device for testing purposes; as such steel gears were chosen to combine the good mechanical properties of steel at a relatively low cost.

2.2. Clutch

The clutch connects the alternator shaft to the input shaft with a clutch ratio chosen to be 10:1. The distance between the sprockets is 25 cm. The force angle is calculated to be $\alpha = 10°$. The pulley of the clutch is made of polyamide with a density of $1430\ kg/m^3$. The clutch is sketched in Fig. 5.

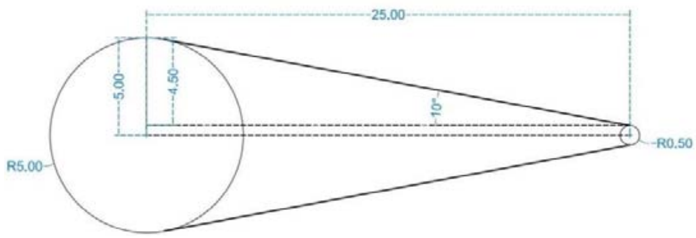


Fig. 5. Sketch of the clutch

2.3. Flywheel

The flywheel is needed to conserve the mechanical energy and to stabilize the rotation of the shaft. The design method of the flywheel is discussed in details in reference [18]. The mass of the flywheel is calculated to be 7 kg and its radius is 13 cm with a thickness of 1.5 cm.

2.4. Shaft

The shaft to which all the aforementioned components are attached is sketched in Fig. 6.

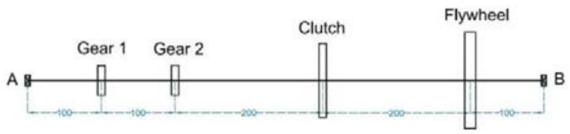


Fig. 6. Sketch of the shaft with different components

A solid shaft of circular cross section is used in the device. The length of the shaft is $700\ mm$ with a diameter of $20\ mm$. The shaft is made of steel $1006\ HR$, with $S_{ut} = 300\ MPa$ and $S_y = 170\ MPa$.

Considering all forces acting on the shaft, critical loads and corresponding critical sections were identified. It is very important and in order to ensure safe operation of the shaft to check for static as well as fatigue failure. The factor of safety against yielding was computed, using the distortion energy criterion (Von Misses), and found to be 2.71. The factor of safety against fatigue was calculated, using the DE-Gerber criterion [19], and found to be 2.91. Both factors of safety are acceptable and this guarantees a safe operation of the shaft.

2.5. Ball Bearings

Bearings are needed to hold the shaft as well the alternator to the wooden support as shown in Fig. 3. Both ball bearings and roller bearings can be used for such application but since only radial loads exist, deep groove ball bearings were chosen. This choice is based on the fact that deep groove ball bearings run with less friction compared to the angular contact ball bearings [20]. The bearings used in the design are of the 02-series type with a bore of 20 mm.

2.6. Float

The component that drives the whole system is the float (buoy) under the action of several forces, the most important of which is the force induced by the surface wave. The float is designed to be of spherical shape and is half-submerged with a diameter of $0.5\ m$.

3. Results and Discussions

The proposed wave energy converter is manufactured and assembled as shown in Fig. 7 and Fig. 8 below. The system was tested on the Lebanese shore where the water depth is around 1.0 m (see Fig. 9).

Fig. 7. Top view of the wave energy converter

Fig. 8. Side view of the wave energy converter

Fig. 9. Wave energy converter in testing

On the day of the testing and as Fig. 9 shows, the surface waves' heights were not significant and this affected the forces exerted on the float itself. Nevertheless, the system operated as expected, the float was heaving upward and downward as expected and the 3-W lamp that was attached to the alternator did light up (see Fig. 9). The system was kept running for around 10 minutes with no real problems. It was noticed that the rack and pinion were experiencing relatively large frictional forces which affect the efficiency the whole system. In fact, the efficiency of the proposed system is computed to be about 11% which is considered quite low. The test was successfully repeated twice, and on two different days, but the wave conditions did not change. In fact, the wave conditions during the month of June do not change much, but the device would work in spite of that.

It is important at this point to mention that this device is still in its early stages and is meant to be a proof of concept. There is room for many improvements (work in progress). The most significant and important improvement is to reduce the friction experienced in the rack and pinion. In addition, the lateral forces exerted by the waves on the float were ignored during the design stages. These forces and due to the relatively long racks have created significant moments on the gears and this also has contributed to lowering the efficiency of the system. One possible solution to this problem (currently being assessed) is to channel the flow of the waves through a cylinder covering the racks and the float in such a way that only vertical forces are exerted on the float.

Finally and since this device will be installed and used in the sea, humidity and most importantly, sea water will be a major concern when choosing the material to be used for the different components. In this device, steel was used and should be replaced by better non-corrosive material or, where applicable, composite materials (next stage of the project) when the device is ready to be mass produced. The float, which will be in direct contact with the sea water, should be regularly maintained by applying anti-corrosion coating on it.

4. Conclusion

A wave energy converter device is proposed in this paper. This device exploits the surface wave forces to produce a heaving motion that is transformed into a rotating motion through a rack and pinion system. The rotational motion is used to produce clean electrical power through an inverter and light up a 3-W lamp. A first prototype of the system is designed, manufactured, assembled and tested in shallow water near the Lebanese shore. The efficiency of this system is relatively low as shown in the previous section, but this can be improved as explained in the same section.

For future work, this system will be embedded in a hybrid system that generates electricity from both wave and wind (through wind turbines).The hybrid system is expected to produce a significantly larger power output with an improved efficiency. This will have a huge impact on the environmental as well as on the economical level, especially in countries like Lebanon where electricity production is a major issue.

Acknowledgements

This project is supported by the National Council for Scientific Research (CNRS), Lebanon.

References

[1] J. Cruz, “Ocean wave energy, current status and future perspectives,” *Green Energy and Technology, Springer*, 2008, p. 461.

[2] J. Falnes, “A review of wave-energy extraction,” *Marine Structures*, vol. 20, 2007, pp. 185-201.

[3] M. Sánchez, R.Carballo, V. Ramos and G. Iglesias, “Tidal stream energy impact on the transient and residual flow in an estuary: A 3D analysis,” *Applied Energy*, vol. 116, 2014, pp. 167–177.

[4] S. Bozzi, R. Archetti and G. Passoni, “Wave electricity production in Italian offshore: A preliminary investigation,” Renewable Energy, vol. 62, 2014, pp. 407-416.

[5] R. Sabzehgar and M. Moallem, “A review of ocean wave energy conversion systems,” *Proceedings of the IEEE Electrical Power and Energy Conference,* 2009, pp. 1-6, Montreal, Canada, October 22-23, 2009, doi:10.1109/EPEC 2009.5420927.

[6] A. Clément, P. McCullen, A. Falcao, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewis, K. Nielsen, S. Petroncini, M. T. Pontes, B. O. Schild, P. Sjöström, H. C. Søresen, T. Thorpe. “Wave energy in Europe: current status and perspectives,” *Renew. Sust. Energy Rev.*, 2002, 6(5), 405–431.

[7] J. Falnes. “A review of wave-energy extraction,” *Mar. Struct.*, vol. 20, 2007, pp. 185-201.

[8] J. P. Kofoed, P. Frigaard, M. Kramer. “Recent developments of wave energy utilization in Denmark,” *Proceedings of the Workshop on Renewable Ocean Energy Utilization,* 2006.

[9] M. Mohammadi, S.H. Hosseinian, G.B. Gharehpetian. “Optimization of hybrid solar energy sources/wind turbine systems integrated to utility grids as microgrid (MG) under pool/bilateral/hybrid electricity market using PSO,” *Solar Energy*, vol. 86, 2012, pp. 112-125.

[10] S.S. Dihrab, K. Sopian. “Electricity generation of hybrid PV/wind systems in Iraq,” *Renewable Energy*, vol. 35, 2010, pp. 1303-1307.

[11] D. Yamegueu, Y. Azoumah, X. Py, N. Zongo.“Experimental study of electricity generation by Solar PV/diesel hybrid systems without battery storage for off-grid areas,” *Renewable Energy*, vol. 36, 2011, pp. 1780-1787.

[12] C. Beels, P. Troch, J.P. Kofoed, P. Frigaard, J.V Kringelum, P.C. Kromann, M.H. Donovan, J.D. Rouck and G.D. Backer, “A methodology for production and cost assessment of a farm of wave energy converters,” *Renewable Energy,* vol. 36, 2011, pp. 3402-3416.

[13] Y. Hong, R. Waters, C. Bostrom, M. Eriksson, J. Engstrom and M. Leijon, “Review on electrical control strategies for wave energy converting systems,” *Renewable and Sustainable Energy Reviews*, vol. 31, 2014, pp. 329-342.

[14] T. Soomere and M. Eelsalu, “On the wave energy potential along the eastern Baltic Sea Coast,” *Renewable Energy*, vol. 71, 2014, pp. 221-233.

[15] P. Mota and J.P. Pinto, “Wave energy potential along the western Portuguese coast,” *Renewable Energy*, vol. 71, 2014, pp. 8-17.

[16] C. Bou-Mosleh, P. Rahme, P. Beaino, R. Mattar and E. Abi Nassif, “Contribution to Clean Energy Production Using a Novel Waver Energy Converter”, *Proceedings of the International Conference on Renewable Energies for Developing Countries – REDEC 2014*, pp. 108-111,Beirut, Lebanon, November 26-27, 2014. doi:10.1109/REDEC.2014.7038540.

[17] N.S. Aouna, H.A. Harajlib and P. Queffeulou, “Preliminary appraisal of wave power prospects in Lebanon”, *Renewable Energy,* vol. 53, 2013, pp. 165–173.

[18] Flywheel Design Calculation - Simplified. (2014, November 16). Retrieved April 5, 2015, from: http://blog.mechguru.com/machine-design/flywheel-design-calculation-simplified

[19] Budynas, R. Nisbet, K.. Shigley’s Mechanical Engineering Design. *McGraw Hill Higher Education, 2011*, 9th Revised edition. ISBN-13 978-0071311137.

[20] Estimating the frictional moment. (n.d.). Retrieved March 1, 2015, from http://www.skf.com/group/products/bearings-units-housings/ball-bearings/principles/friction/estimating-frictional-moment/index.html